4-23-2010

Multi-Scale Analysis of Landscape and Geomorphic Controls on Stream Habitat Structure

Andrew M. Sanderson

To the University Council:

The Thesis committee for Andrew Michael Sanderson certifies that this is the approved version of the following thesis:

Multi-Scale Analysis of Landscape and Geomorphic Controls on Stream Habitat Structure

Hsiang-te Kung, Ph.D.
Major Professor

Esra Ozdenerol, Ph.D.

Gregory Nathaniel Taff, Ph.D.

Accepted for the Council:

Karen D. Weddle-West, Ph.D.
Vice Provost for Graduate Programs

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Memphis, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature____

Andrew Michael Sanderson

Date________________April 21, 2010________________

MULTI-SCALE ANALSYIS OF LANDSCAPE AND GEOMORPHIC CONTROLS ON STREAM HABITAT STRUCTURE

by

Andrew Michael Sanderson

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Major: Earth Sciences

The University of Memphis

May 2010

Acknowledgements

I thank my advisor Hsiang-te Kung for his vital encouragement and support and insight over the past few years; committee members Esra Ozdenerol and Gregory Taff for their comments and guidance on geographic techniques and statistical methods; Arleen Hill and Thad Wasklewicz for their early role in advising and shaping the direction of this research. My graduate studies were funded by The University of Memphis Department of Earth Sciences through a teaching assistantship, enabling the necessary information and resources to inform the completion of this thesis. Most special thanks go to my family and friends whose constant encouragement and inspiration will never be forgotten.

Abstract

Sanderson, Andrew Michael. M.S. The University of Memphis. May 2010. Multi-Scale Analysis of Landscape and Geomorphic Controls on Stream Habitat Structure. Major Professor: Hsiang-te Kung

Landscape and geomorphic characteristics within watersheds in the North and South Umpqua Basins in Southwestern Oregon were summarized at five spatial scales (basin, sub-basin, network, sub-network, and segment) and incorporated into multiple regression models to determine the relative effects of each on stream morphology and provide a potential predictive model of stream habitat characteristics using GIS-managed landscape variables. Measures of stream morphology included mean stream depth, mean corrected width, width-to-depth ratio, percent shade provided to habitat units, and substrate composition, summarized for 200 stream segments. While certain variables were demonstrated to have a consistent influence across more than one scale, the scale-dependency of other relationships between landscape and stream characteristics was revealed between the vegetation, lithology, and geomorphology and measures of stream morphology. Stream dimensions were most sensitive to variability in the size of analytical unit (drainage basin/sub-basin or riparian buffer) and the relative presence or absence of vegetation as represented by the percentage area of each analysis unit encompassed by open and semi-closed canopy cover. Stream substrate material composition was related most strongly to drainage density, topographic complexity, and steepness of land within each analysis unit. Such methods proved helpful in determining to what degree and at which scale the included landscape variables operated.

Table of Contents

List of Tables

Introduction and Literature Review

While linkages among catchment landscape characteristics and the quality and function of its watercourses are recognized as vital to the health of aquatic ecosystems, only recently have attempts been made to determine these elements interact across various spatial extents. This thesis builds upon a growing body of work that explores the linkages between landscape and stream morphology by addressing how watershed topography, geology, and landcover characteristics may influence the dimension and distribution of stream habitat structure throughout its streams. Concepts and methods from previous studies are incorporated into this thesis in order to provide an overview of some of these linkages. Zonal statistics were extracted at five hierarchically nested spatial extents (based on Burnett, Reeves, Clarke, and Christansen, 2006) and entered as independent variables in multiple regression models comparing those landscape variables to stream habitat dimensions. Eight stream variables are each modeled against fifteen landscape variables at each of the five extents ranging from three riparian to two watershed scale extents, uncovering the relative influence of landscape variables and those representing stream habitat dimensions and confirming expectations that significant correlations between landscape variables and stream habitat measurements exist. Several landscape – stream linkages persist independently of scale while others appear more sensitive to changes in the analysis scale extents. The inferred relationships, both direct and indirect, provide a framework for further investigation of landscape impacts on stream habitat and the interaction among those parameters and aquatic life.

Influence of Spatial Pattern on Process

The interconnectedness of riverine landscapes and the linkages between biotic and abiotic environmental variables within watersheds influence the character of streams. Much of the rationale for river basin management derives from the idea that a catchment is a topographically and hydrologically defined unit (Allan, Erickson, & Fay, 1997). Rivers and lakes are strongly influenced by the geology, basin topography, and vegetation of their respective watersheds, but there is only limited understanding of how these interrelate (Allan & Johnson, 1997). Furthermore, biodiversity patterns are directly and indirectly influenced by the geomorphology of riverine landscapes which may be perceived as a nested hierarchy wherein the characteristics of the watershed determine physical processes that ultimately affect the character of streams (Ward, 1998). These physical processes are responsible for maintaining the structural features of fluvial hydrosystems whose characteristics govern the volume and quality of the aquatic environment (Petts & Gurnell, 2005; Yarnell, 2006). The landscape influences its water bodies through multiple pathways and mechanisms, operating at multiple spatial scales and only recently have attempts been made to address these complex relationships (Allan, 1997; Burnett et al., 2006).

In order to examine the interplay of landscape elements with those essential to stream habitat, it helps to break the landscape down into component parts (the same is true for any system). The perception of the landscape as a nested hierarchy allows for a structured approach designed to zero in on variables that may be appear as noise in broader scales of analyses or to uncover trends suggest broader scale process are influencing outcomes in an area of interest (Figure 1). The intent of this thesis is to gauge relationships at a variety of scales in an effort to determine the appropriate scale(s) of analysis for each independent variable when modeled against the stream habitat metrics chosen. For example, one hypothesis employed in formulating the approach used here is that those processes responsible for sediment supply (i.e., vegetation coverage and type) will be more important at the more local, riparian scale and less pronounced at the broader spatial extents, hence the varying scope of analysis that utilizes three progressively larger riparian extents and two similarly nested catchment extents.

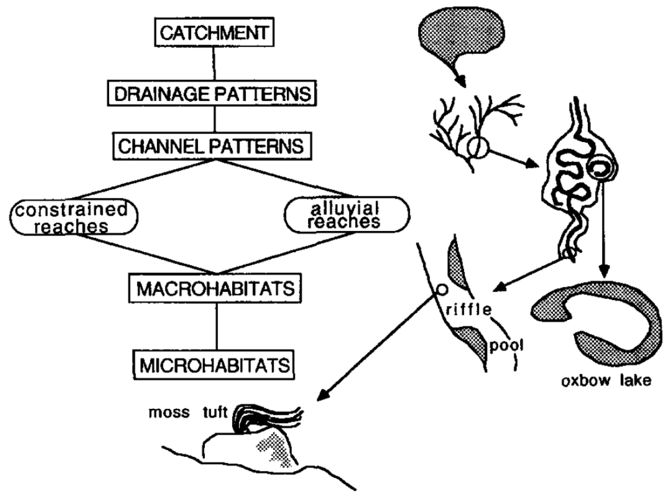

Figure 1. A geomorphic hierarchy of riverine landscapes

Source: Ward, J.V., 1998. Riverine Landscapes: Biodiversity Patterns, Disturbance Regimes, and Aquatic Conservation. *Biological Conservation, 83 (3), 269 – 278.*

Influence of Basin and Riparian Geomorphology

Topography affects the hydrological functioning of riparian zones and the slope gradient at the riparian zone – upland margin influences the hydraulic gradient and the volume and velocity of water entering the riparian zone (Vidon & Hill, 2004). Nichols, Killingbeck, and August (1998) found that biotic and geomorphic heterogeneity were intricately linked at the landscape scale in a study of plant communities in Rhode Island. In a previous study, it was found that convergent patterns of geomorphic heterogeneity and woody plant species diversity support the hypothesis that biotic diversity is a function, in part, of environmental diversity (Burnett, August, Brown, & Killingbeck, 1998). Topographic complexity also proved to be a significant landscape variable for predicting stream water quality, explaining 75% of variability in benthic macroinvertebrate tolerance from stream degradation at both the watershed and riparian scale (Potter, Cubbage, & Schaberg, 2005). Furthermore, Lanka and Wesch (1987) and Huryn and Wallace (1987) demonstrated significant relationships between stream habitat and geomorphic variables.

Two studies (Burnett et al., 1998; Nichols et al., 1998) influencing the conceptual framework of this thesis involved the tendency for topographically complex terrain to have an increased diversity of woody plant species diversity. One must look no farther than the Southern Appalachians for another example of the notion that richer habitats can result from a more varied and complex physical setting (Morse, Stark, & McCafferty, 1993). The combination of climate and the variability in terrain inherent to this region make it one of the most botanically diverse regions in the world. It is no stretch of imagination to entertain the notion that botanical diversity could possibly be linked to the health of aquatic ecosystems in both the structural and chemical sense. While this thesis does not delve into extreme detail regarding terrestrial plant diversity, an effort is made to incorporate the relative presence or absence of vegetation and type of canopy cover. Using categories of open, semi-closed canopy and scrub and denser forest coverage of broadleaf and mixed broadleaf/coniferous canopy cover (>70%) enables an opportunity to model the influence of vegetation cover alongside the influences of landform, underlying rock material, and the various other geomorphic measurements included in the models.

Importance of Habitat Structure

Habitat structure may be loosely defined as the spatial distribution of habitat features across the landscape (or, in this case, "river- or streamscape"). Riverine habitat heterogeneity – the inherent diversity of aquatic habitats throughout a stream environment – has become recognized as a key attribute in understanding river ecosystems (Power 1992; Yarnell, Mount, & Larsen, 2006). Fish tend to specialize on specific habitat types and the fish community characteristics of a segment of stream are determined by the complexity of habitat present (Gorman & Karr, 1978). Moreover, diversity in stream habitat provides not only a greater range of niches for species to occupy, but provides a greater variety of habitats available to species for breeding, foraging, and refugia (Allan & Johnson, 1997; Ward 1998; Ward & Tockner, 2001; Yarnell et al., 2006). Since geomorphology and hydrology are the physical foundation of stream ecosystems, it seems apparent that aquatic habitat characteristics would vary widely according to landscape characteristics at multiple scales. However, questions remain as to which terrain characteristics play a dominant role in determining the dimensions of the aquatic environment and the scale at which such variables operate.

Since habitat structure implies the spatial arrangement of the various physical parameters that make up the ‘built’ stream-scape, certain variables were chosen that represent multiple dimensions of that space. The most apparent variables of form are the depth, width, and width-to-depth ratio of stream habitat units, which control the shape and volume of the object of interest. Percent of shade provided to habitat units was also summarized. While not an entirely tangible dimension of the stream environment, the amount of insolation received by a given habitat unit undoubtedly affects the suitability of said unit by controlling water temperature and, ultimately, the chemical composition of the water contained in the unit at any give time. This goes without saying that temperature most obviously affects the physical environment in terms of which species can and cannot tolerate high water temperatures. For the purposes of this thesis, the shade measurement can be conceived as a proxy to myriad process dependent upon insolation of the aquatic environment. Another indispensable component of physical habitat structure incorporates the relative presence of substrate material types or, put simply, what the streambed is made of. Categories of substrate material type presented by Gorman and Karr (1978) are modeled here in an effort to determine how landscape controls each. The relative abundance of gravel, cobble, bedrock, and finer grained sand-silt-organic type streambed compositions are defined in the methods section. Important in terms of the form and availability of environments utilized by all types of species for refugia, foraging, and reproduction, substrate material cannot be ignored when considering the form and function of the aquatic environment. In summary, habitat heterogeneity itself is not analyzed herein, but the models developed herein attempt to determine landscape controls on the structural aspect of stream environments and provide a glimpse of how the various elements that determine the quality and arrangement of that environment are influenced on an individual basis. Analysis of spatial patterning and in-stream relationships must be reserved for a subsequent study.

Multiple Analysis Scales

The use of multiple scales of analysis allow for the detection of the spatial relationships both within and among various spatial extents. Analysis of multiple, hierarchical scales serves to address the modifiable areal unit problem (Hay, Dubé, & Bouchard, 2001, 2002). Such an approach of sensitivity analysis allows additional insight into the scale at which certain processes operate by determining which variables are sensitive to variations in scale configuration (Jelinski & Wu, 1996). This requires that the data used be hierarchically nested and that results can be obtained for each hierarchical level (Marceau & Hay, 1999). While there is no set of rules by which to scale information, analysis at multiple scales has proven to be an effective method by which to address the issue of scale sensitivities (Jelinski & Wu, 1996; Marceau & Hay, 1999). Since there is no inherent appropriate scale by which to compare terrain variability to structural variability in streams, terrain statistics at each of five spatial extents will be summarized to represent each of five spatial extents and compared with the stream extents that represent the respective catchment's areas. A more detailed description of this approach follows in this text.

Study Area

The study area is located in the Umpqua River Basin (Figure 2), primarily in Douglas County of Southwestern Oregon, and covers an area of 11,834 km2. Three distinct geographic regions are identified in the Umpqua basin—the Klamath Mountains, the Coast Range Mountains, and the Western Cascade Mountains. The Klamath Mountains are characterized by very rugged terrain with elevations ranging from 500 to 5,000 feet. Steep slopes and v-shaped valleys dominate the landscape. The Coast Range is characterized by small mountains and hills with elevations ranging from sea level at the Pacific Ocean to upwards of 3,300 feet. The Western Cascades exhibit gently sloping plateaus to steep side slopes. Elevation ranges from 800 to 5,000 feet. Climate in the Umpqua Basin is governed by the varied landscape, which can also be divided into three general regions: the Coast Range, Southwestern Interior, and Cascade Mountains. Streams in the Umpqua basin are home to a variety of freshwater and anadromous fish. Rainbow trout, brown trout, cutthroat, and other game fish are found throughout streams in the Umpqua Basin. The region is best known for its steelhead and salmon fisheries, which are a big draw for sport fishermen. Two fishing seasons occur annually due to the migration of steelhead trout (an anadromous form of rainbow trout), Chinook and Coho Salmon.

Research Objectives

The relative strength and scale-dependence of linkages between catchment landscape elements and stream morphology are tested through the use of GIS-managed variables. Three objectives are addressed by the methods employed herein:

1. Determine which terrain variables most readily explain variability in stream morphology dimensions.
2. Highlight which of those relationships are sensitive to variations in the scale of analysis.
3. Measure and compare the strength of statistically significant variables and determine the effect of scale on those measurements.

While among-scale relationships among landscape variables to stream characteristics were suggested in a previous study (Burnett et al., 2003), interactions of landscape variables across various scales were not tested due to time constraints. This study moves this field of research forward by analyzing in depth how landscape variables influence stream characteristics at multiple scales. The scale dependencies measured here may provide a framework by which to understand in more detail how certain elements interact across the landscape. Furthermore, once these relationships are established, the influence of spatial pattern upon aquatic species' health and behavioral patterns may be more easily approached, leading to a more comprehensive understanding of how the physical parameters of watersheds and riparian zones impact the biological integrity of streams.

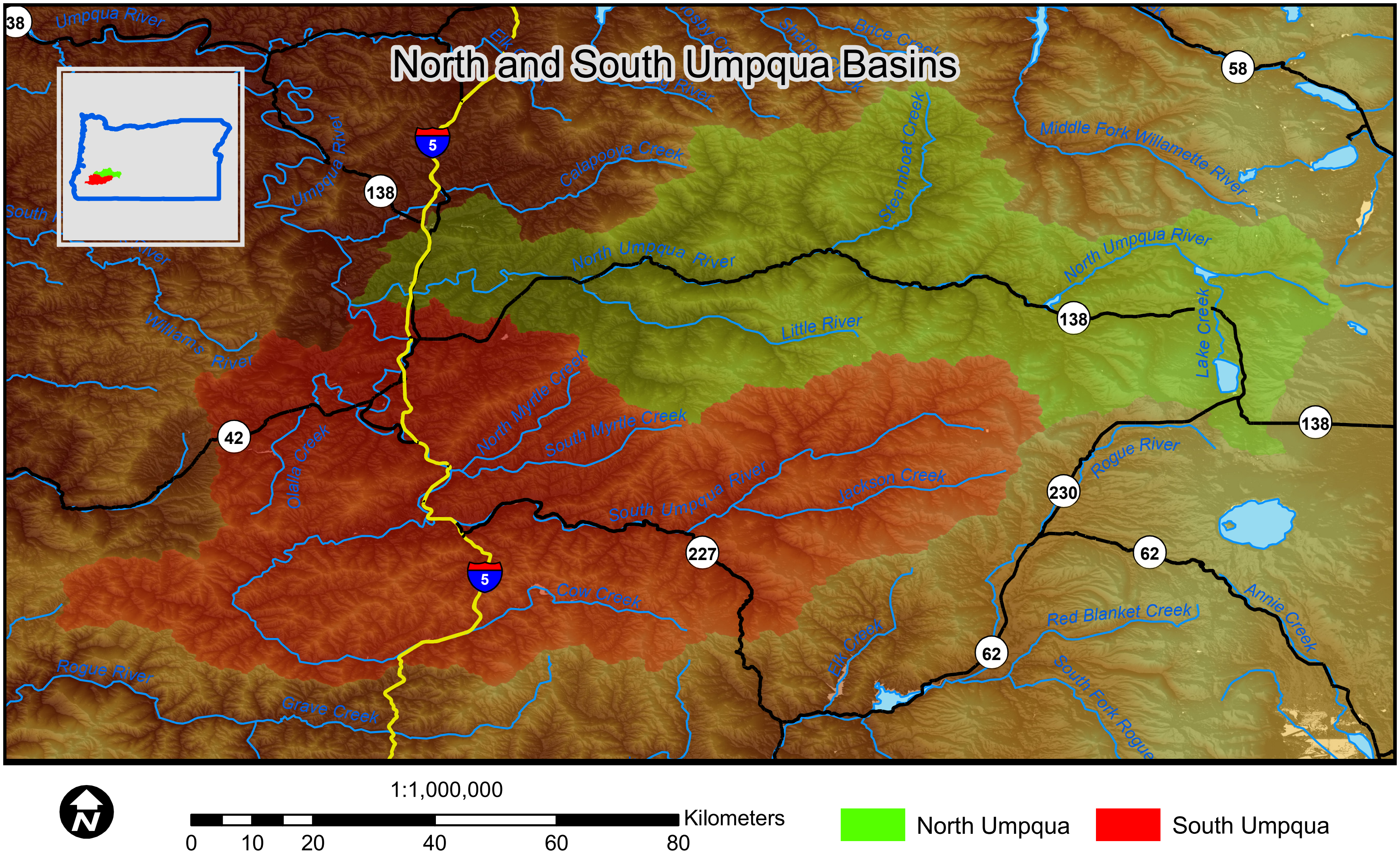

Figure 2. Study Area

Methods

All spatial data were handled using ESRI ArcGIS version 9.2 (ESRI, Inc., Redlands, California) and all statistical procedures were performed using SPSS version 17 (SPSS Inc., Chicago, Illinois). Summary statistics were generated at five analytical scales for 200 streams within the North and South Umpqua River Basins to compare the potential influence of landcover and geomorphic properties on stream morphology within each watershed at multiple scales. Hydrographic data were summarized by unique identifiers from 30,345 habitat units collected by the Oregon Department of Fish and Wildlife. Landcover and geomorphology data were summarized at each of the following five analytical scales: Watershed, Sub-Watershed, Network, Sub-Network, and Segment (Figure 1). Variables from each uniquely identified stream segment were then spatially joined to their respective analytical units from which values were tabulated and used to develop multiple regression models for each stream habitat variable at each scale.

Data Sources

Vector and raster data were generated using a variety of sources at differing scales, using different coordinate systems and projections (Table 1). These data were easily reconciled into a common coordinate system and projection, but the primary concern lay in the original data compilation methods. Error due to spatial inaccuracy is inevitable when reconciling data derived from smaller scale sources and raster data of coarser resolutions. In the most ideal circumstances, all data would be derived from a scale of 1:24,000 or larger, but spatial accuracy was sacrificed in order to accommodate the use of available data.

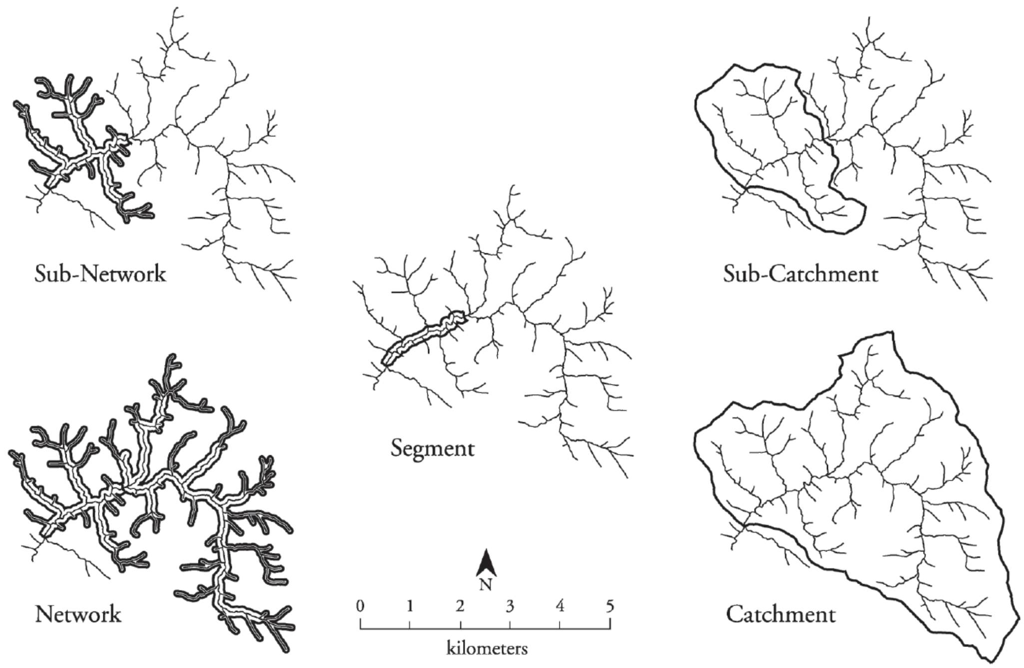

Figure 3. Analytical Units.

Source: Burnett, Kelly, M. Gordon H. Reeves, Sharon Clarke, and Kelly R. Christiansen, 2006. Comparing Riparian and Catchment Influences on Stream Habitat in a Forested, Montane Landscape*. American Fisheries Society Symposium, 48, 175 – 197.*

Stream habitat survey data, compiled by the Oregon Department of Fish & Wildlife was georeferenced to 1:100,000 coverages originally digitized by the USGS as part of the Pacific Northwest River Reach Project. Stream habitat surveys incorporated a combination of field survey methods wherein habitat unit and reach data were geographically linked in-field using topographic maps and/or GPS units. The data were subsequently georeferenced and entered by stream basin based on hydrologic unit codes defined by the Environmental Protection Agency (ODFW, 2004). A complete description of the field survey methodology is outlined in Moore, Jones, and Dambacher (2002). Variables derived from the stream habitat data include reach depth, average width, width-to-depth ratio, percentage shade provided to habitat units, and streambed composition. Coarser scale data were easily reconciled to a more accurate 1:24,000 scale hydrography dataset based on the hydrologic unit codes common to both datasets.

Table 1

Data Sets and Corresponding Scale, Format, and Source Descriptions.

Data	Scale / Resolution	Format	Description
Hydrography	1:100,000	vector	Stream reach and habitat unit survey data
	1:24,000	vector	Accurately mapped stream layer. Includes common hydrologic unit code with stream habitat dataset. Also describes fish presence within stream segments.
Geology	1:500,000	vector	Spatial digital database for the geologic map of Oregon.
Elevation	10 meter	raster	Digital elevation data. Used to delineate drainage basins and derive slope raster.
Landcover	30 meter	raster	2001 era Landsat 7 Thematic Mapper - Used to estimate forest cover type.
Canopy Cover	30 meter	raster	2001 era Landsat 7 Thematic Mapper - Used to estimate canopy cover density.

The geology dataset was derived from sources varying from 1:100,000 – 1:1,000,000 hardcopy maps and was not intended for use at significantly higher scales. While the unit polygon attribution reflects the original source maps' unit information, using this data at a larger scale can introduce considerable error. However, upon inspection of the geology data in the area of interest, it was determined that its spatial accuracy was adequate to extract the desired metric at each analytical unit. The geology coverage was further generalized to reflect the predominant lithology (igneous, metamorphic, sedimentary, or unconsolidated fill) for the study area.

The largest scale digital elevation data available for the Umpqua Basin was 1/3 arc-second (approximately 10 meters) Arc Grids from the National Elevation Dataset (seamless.usgs.gov). These were downloaded in 250 megabyte segments and mosaicked into a single seamless coverage to cover the extent of the study area. The DEM was used to derive a slope raster, drainage basin relief, and topographic complexity (standard deviation of elevation). The 1/3 arc-second resolution exceeded the spatial accuracy needs of the 1:24,000 scale stream coverages.

Landcover data were derived from 2001 era Landsat 7 Thematic Mapper and Landsat Enhanced. The author combined Landcover and canopy cover rasters using the overlay function in ArcMap in order to estimate canopy density by forest type (Table 3). The spatial resolution of both Landsat datasets was 30 meters.

Raster data projections and transformations are more problematic than for vector data. Projecting raster data requires a resample of grid information, which introduces distortions in the shape and area of categorical data. Since each dataset was stored using differing coordinate systems, reconciliation with the vector data was achieved by leaving the raster data in its native format. The vector analytical unit coverages were instead converted to the coordinate system used for raster data in order to minimize error due to spatial inconsistencies. This method was not cumbersome due to the limited number of reference systems used.

Table 2

Dependent Variables and Corresponding Descriptions.

Dependent Variables	**Description**
stream data	
Average reach depth	Average depth of habitat units (m). Measured as modal depth in fast water units and maximum depth in slow water units.
Average Width	Average width of stream
Width : Depth Ratio	Ratio of active channel width to active channel depth
% shade	measures the amount of shade provided to the habitat unit from vegetation and topography
% silt - sand	percentage of substrate composed of sand, silt, and organics
% gravel	percentage of substrate of gravel size class (2 - 64mm in size)
% cobble	percentage of substrate of cobble size class (64 - 256mm in size)
% bedrock	percent of habitat unit substrate identified as bedrock

Table 3

Independent Variables and Corresponding Descriptions.

Independent Variables	
geomorphology	
Area	Area of analysis units (square meters). Calculated from drainage polygons and buffers using ArcMap.
Basin Perimeter	Perimeter of drainage (meters)
Compactness Coefficient	basin perimeter / [2(3.14 x basin area)$^{1/2}$]
Channel Slope	Average gradient of habitat unit water surfaces. Measured as a percent change in elevation over each unit.
Drainage Density	Length of all flowing streams in an analysis unit divided by area of that unit (e.g., drainage basin (m) / drainage basin area (m^³)
Basin Relief	Highest elevations on the headwater divide minus the stream segment elevation.
Relief Ratio	Basin relief / stream length
Topographic Complexity	Standard deviation of elevation in analytical unit.
landcover	
Slope Class ≤ 30%	Percent area of analytical unit with an average surface slope less than or equal to 30 percent.
Slope Class 31 - 65%	Percent area with an average slope from 31 to 65%
Slope Class > 65%	Percent area with an average slope greater than 65%
Open and Semi-closed Canopy	Percent area with < 70% tree cover
Broadleaf Canopy	Percent area > 70% deciduous and shrub cover.
Mixed Broadleaf-conifer forests	Percent area > 70% deciduous and conifer tree cover
lithology	
Sedimentary Rock	Percent area of units predominated by sedimentary rock
Metamorphic Rock	Percent area of Metamorphic Rock
Igneous Rock	Percent area of Igneous Rock

Spatial Data Processing

Analytical Units. Analytical units were generated following the methodology used by Burnett et al. (2006). Five analytical units for each stream were generated for each stream segment – two drainage basin scale (basin and sub-basin) and three riparian scale (network, subnetwork, and segment). The analytical unit polygons were spatially joined to the appropriate stream segment, which tagged them with a hydrologic unit code that allowed corresponding landscape data (Table 3) to be related to the correct stream morphology data. The boundaries of each analytical unit were used to derive zonal statistics at each of five scales per stream.

Drainage basin boundaries were extracted from the DEM using ArcGIS Spatial Analyst. Basins were based on pour points placed near the terminus of streams identified by the hydrologic unit code in its attribute table. Sub-basin boundaries, which were subsumed by basins, contain the area of the larger basin where tributaries were orthogonal to the main stream segment. Sub-basins were delineated by adding pour points those used in the first step at the location just upstream of the orthogonal tributaries' catchments. This step divided watersheds into areas upstream and downstream of the additional pour points. The upstream polygons were removed from the layer, resulting in the sub-basin layer.

Riparian scale buffers were based on Riparian Reserve widths used by Burnett (2006) and are described in the report of the Forest Ecosystem Management and Assessment Team (FEMAT, 1993). The 1:24,000 Oregon Department of Forestry stream data was used to identify fish-bearing stream segments. One hundred meter buffers were generated for fish-bearing segments and fifty meter buffers were generated for non-fish bearing segments. Network buffers encompassed all tributaries within drainage basins, while sub-network buffers encompassed tributaries draining orthogonally into the stream segment and were contained by sub-basins. Stream segment buffers were the smallest analytical unit, bounded upstream by the sub-basin boundary and the stream terminus.

Geomorphic and Landscape Data Preparation. All raster data were maintained in their native projections. The digital elevation model was based on the NAD83 horizontal datum and NADV88 vertical datum. The Landsat data are stored with the NAD83 Albers Conical Equal Area projection. In order to reduce errors in spatial accuracy, vector layers were projected into the coordinate system of the raster datasets before zonal statistics were extracted.

Terrain statistics and a percent slope raster were generated from the digital elevation model. Drainage basin area, perimeter, and compactness coefficient were calculated from the basin polygons generated from the DEM. The compactness coefficient was calculated by dividing the basin perimeter by basin area. Drainage density was calculated by dividing the length of streams in the 1:24,000 hydrography layer within each analysis zone by the area of the analysis zone. Relief ratio was calculated by dividing basin relief (highest elevation – lowest elevation) by the stream length of the longest stream within each basin. The percent slope raster was then reclassified into categories similar to those in Burnett et al. (2006) and Lunetta, Cosentino, Montgomery, Beamer, and Beechie. (1997). Percent area of each slope category was then calculated for each analysis unit.

The Landsat landcover and canopy cover data were used in conjunction to derive percent area of open and semi-closed canopy, broadleaf, and mixed-broadleaf-conifer forest. The open and semi-closed canopy coverages describe areas with less than 70% tree cover. The broadleaf and mixed-broadleaf coverages describe areas with 70% or greater deciduous tree/shrub coverage and mixed conifer and deciduous forests, respectively.

The geology coverages were converted from vector to raster in preparation to extract zonal statistics. To preserve spatial integrity, a three meter resolution was used during conversion. Spot comparisons between the vector and resultant raster revealed that distortion of shape and area of the raster were within an acceptable range. Predominant lithology was derived by reclassifying the geology coverage into categories for sedimentary, metamorphic, igneous, and unconsolidated fill.

Stream Morphology Data. Stream habitat parameters for habitat units were summarized as the average of each variable for streams in the study area: mean depth, mean corrected width, width-to-depth ratio, mean percentage shade, and percentage streambed material type. Depth was originally collected as modal depth in fast water units (glides, riffles, rapids, cascades) and maximum depth in slow water units (pools, backwater). Percentage of substrate material type represents the percentage of each substrate type (Table 2). Habitat units were stored as line segments of streams, each tagged with a unique hydrologic unit code. Those segments were clipped using the segment buffer polygon before calculating summary statistics for stream morphology variables. Data for 200 stream segments were then tabulated and joined to the corresponding five analysis zone data using the hydrologic unit code.

Regression Model Development. Multiple linear regression models were developed for each stream morphology variable within each zone of analysis using backward stepwise regression. Since only a moderate sample size of 200 stream segments was analyzed, adjusted R2 was reported to account for an inflated value for the proportion of variation explained in the regressions due to a larger number of independent variables entered into the model. Bivariate correlations between independent variables ($r > .65$, $n = 200$) that revealed significant pair-wise relationships were omitted from the model in order to avoid introducing multicollinearity.

Regression assumptions (linearity of relationships between dependent and independent variables, normality of errors, and homoscedasticity of errors in relation to X-variables) were verified with normality plots and standardized residual plots. Since a degree of spatial autocorrelation was assumed, independence of observations was not verified. Transformations were necessary for both y- and x- variables in order for the models to meet regression assumptions. Transformed variables and the type of transformation were noted with their corresponding result tables and figures.

Results

Eight stream habitat variables were analyzed for 200 streams at five scales. Some explanatory variables were omitted due to significant bivariate correlations ($R \geq .65$) with other explanatory variables. Basin perimeter and relief were omitted from all models due to large, significant positive correlations with Analytical Unit Area and topographic complexity, respectively. Percent area with slope below 30% was omitted from the network, sub-basin, subnetwork, and segment scales because large, significant positive correlations with percent of slope between 30% and 65% and percent of slope over 65%. Percent area of sedimentary rock types showed large, significant negative correlations with both percent areas of metamorphic and igneous rock types, and was omitted from all scales except the basin scale. Percent area with broadleaf canopy coverage was omitted from the subnetwork scale models due a large, significant negative correlation with percent area mixed forest canopy cover. There was little multicollinearity in any model (each VIF < 2). No more than five outliers were removed from several models, but doing so resulted in no more than a change of 5% in proportion of variance explained by the models. All explanatory variables are reported, however those with p-values greater than .05 are indicated. Table 4 shows R^2 values for each model.

Table 4

Adjusted R^2 Values. (Ln) or (sqrt): Natural logarithm or square-root transformation on y-variable.

	depth	width	Width – depth ratio	shade	gravel	cobble	bedrock	sand, silt, organics
basins	.574	.686 (*Ln*)	.068 (*Ln*)	.262	.222 (*Ln*)	.261	.165	.356 (*sqrt*)
networks	.470	.581(*Ln*)	.094 (*Ln*)	.217	.171 (*Ln*)	.182	.105	.299 (*sqrt*)
sub-basins	.410	.568 (*sqrt*)	.110 (*Ln*)	.198 (*sqrt*)	.202 (*Ln*)	.198	.101	.301 (*sqrt*)
sub-networks	.515	.668	.063 (*Ln*)	.216 (*sqrt*)	.204 (*Ln*)	.073	.074	.184 (*sqrt*)
segments	.451	.463 (*Ln*)	.110 (*Ln*)	.216	.177 (*Ln*)	.037	.109	.163 (*sqrt*)

Table 5 lists unstandardized coefficients for mean depth models at each scale. Significant ($p \leq .05$) positive relationships between Analytical Unit Area and mean depth were found at all scales. A natural logarithmic transformation was applied to the Analytical Unit Area variable at the basin, network, and sub-basin scale for conformity to regression assumptions. Analytical unit area was positively correlated to mean depth at all analysis scales and also had the most weight in models at each scale. Percent area in open and semi-closed canopy was negatively related to mean depth at all scales. Topographic complexity showed a positive relationship with depth at the network, sub-basin, and sub-network scale. Mean channel slope was negatively related to depth at the sub-network and segment scale. Relief ratio and percent of area with mixed broadleaf and coniferous canopy coverage were only significant in the basin scale model with a positive and negative relationship with depth, respectively. Percent areas in the 31 – 65% slope category were significant in the sub-basin and sub-network scales, showing a negative relationship with depth. Percent area with unconsolidated geologic materials was significant only at the segment scale, showing a positive relationship with depth.

Table 5

Unstandardized Coefficients for Mean Depth Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	**Networks**	**Sub-Basins**	**Sub-Networks**	**Segments**
(Constant)	-1.484	-.836	-.467	.340	.245
Analysis Unit Area	.119 (.765) [*Ln*]	.075 (.504) [*Ln*]	.055 (.448) [*Ln*]	7.37×10^{-2} (.352)	1.541×10^{-7}(.582)
Compactness Coefficient	-.095 (-.092)				
Channel Slope		.000 (-.111) *		-.001 (-.167)	-.002 (-.216)
Drainage Density					
Relief Ratio	.148 (.142)				
Topographic Complexity		.001 (.260)	.001 (.221)	.001 (.397)	
Slope < 30% (% Area)					
Slope 31 - 65% (% Area)		-.124 (-.104) *	-.187 (-.160)	-.267 (-.240)	
Slope > 65% (% Area)					.193 (.195)
Open/Semi-Closed Canopy (% Area)	-.103 (-.135)	-.142 (-.205)	-.095 (-.157)	-0.097 (-.168)	-.118 (-.246)
Broadleaf Canopy					
Mixed Canopy (%Area)	-.747 (-.186)				
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock					.037 (.106) *
Unconsolidated Geology					.118 (.141)

Mean Width

Models for mean width of habitat units demonstrated the highest proportions of explained variance of any stream habitat model (R^2 ranged from .463 – .686). Natural logarithmic transformations of mean corrected width were required at the basin, network and segment scales while a square root transformation was required at the sub-basin scale. A positive relationship was shown between width and area of analytical unit for all scales (Table 6). Analytical unit area also accounted for the most variation of mean width at all scales. Percent area in open/semi-closed canopy was also significant in models at all scales, showing a negative relationship with mean width. Topographic complexity was positively related to mean width at the basin, network, sub-basin, and sub-network scales. Channel slope was shown to be negatively related to mean width at the basin, sub-network, and segment scales. Drainage density, percent area in less than 30% slope, and percent area in mixed canopy were significant only in the basin scale model, each showing negative relationships with mean width. Percent area in broadleaf canopy was significant only in the sub-basin model, showing a positive relationship with width. Percent area in slope over 65% was significant only in the segment model, showing a positive relationship with width.

Width : Depth Ratio

Area of analytical unit was significant in every model for width-to-depth ratio except for the basin scale, showing a positive relationship in each (Table 7). Relief ratio and percent area in slope less than 30% were significant only in the basin scale model, showing negative relationships in each case. Topographic complexity was significant only at the network and network scale, showing a positive relationship with width-to-depth ratio at each scale. Percent area in open/semi-closed canopy cover was significant in only the sub-network model, showing a positive relationship. Percent area in broadleaf canopy cover was significant only at the sub-basin model, with a positive relationship with width-to-depth ratio. Percent area in igneous rock types was significant in only the sub-network and segment models, with a negative relationship with mean width-to-depth ratio.

Table 6

Unstandardized Coefficients for Mean Corrected Width Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	Networks	Sub-Basins	Sub-Networks	Segments
(Constant)	-4.132	-3.566	-2.123	3.148	1.084
Analysis Unit Area	.331 (.668) [Ln]	.285 (.600) [*Ln*]	.258 (.667)	1.467x10-7(.592)	5.260x10-7 (.621)
Compactness Coefficient					
Channel Slope	-.003 (-.108)	-.002 (-.099) *		-.011 (-.130)	-.004 (-.183)
Drainage Density	-41.659 (-.113)				
Relief Ratio					
Topographic Complexity	.001 (.110)	.003 (.310)	.002 (.176)	.012 (.296)	
Slope < 30% (% Area)	-.255 (-.089)				
Slope 31 - 65% (% Area)			-.350 (-.093) *	-2.303 (-.180)	-.394 (-.140)
Slope > 65% (% Area)					.377 (.119)
Open/Semi-Closed Canopy (% Area)	-.343 (-.140)	-.479 (-.217)	-.240 (-.127)	-.894 (-.135)	-.446 (-.291)
Broadleaf Canopy			.544 (.191)		
Mixed Canopy (%Area)	-1.217 (-.095)				
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock					
Unconsolidated Geology					

Percent Shade

Percent area of open and semi-closed canopy cover was negatively related to percent shade at each scale and also had the most weight in each model. Percent area between 31 – 65% slopes was positively correlated to percent shade at each scale (Table 8). Drainage density was significant in only the sub-basin and sub-network scale models, showing a negative relationship with percent shade in both. Both relief ratio and percent area in slope less than 30% were contained only in the basin-scale model, showing a positive relationship with width-to-depth ratio in both. Topographic complexity was significant only in the sub-basin model, showing negative relationship with the width-to-depth ratio.

Table 7

Unstandardized Coefficients for Width:Depth Ratio Models at all Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	**Networks**	**Sub-Basins**	**Sub-Networks**	**Segments**
(Constant)	1.975	1.132	.930	2.313	2.307
Analysis Unit Area		.067 (.244) [*Ln*]	.089 (.395)	9.48×10^{-9}(.180)	1.434×10^{-7}(.292)
Compactness Coefficient	.227 (.123) *				
Channel Slope					
Drainage Density					
Relief Ratio	-.376 (-.203)				
Topographic Complexity	.001 (.263)	.001 (0.178)			
Slope < 30% (% Area)	-.435 (-.270)				
Slope 31 - 65% (% Area)					
Slope > 65% (% Area)					-.221 (-.120) *
Open/Semi-Closed Canopy (% Area)				.212 (.146)	
Broadleaf Canopy			.320 (.188)		
Mixed Canopy (%Area)			.092 (.123) *		
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock				-.144 (-.156)	-.101 (-.156)
Unconsolidated Geology				-.356 (-.119) *	-.213 (-.137) *

Table 8

Unstandardized Coefficients for Percent Shade Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	Networks	Sub-Basins	Sub-Networks	Segments
(Constant)	65.533	71.822	8.883	10.315	84.588
Analysis Unit Area					
Compactness Coefficient			.572 (.119) *		
Channel Slope		.112 (.126) *			
Drainage Density			-83.057 (-.172)	-151.137 (-.234)	
Relief Ratio	18.108 (.203)				
Topographic Complexity			-.004 (-.268)		
Slope < 30% (% Area)	19.108 (.276)				
Slope 31 - 65% (% Area)	27.798 (.346)	26.439 (.273)	.974 (.189)	1.333 (.272)	8.630 (.127)
Slope > 65% (% Area)					
Open/Semi-Closed Canopy (% Area)	-23.989 (-.407)	-16.846 (-.318)	-1.145 (-.427)	-.819 (-.322)	-14.431 (-.392)
Broadleaf Canopy					
Mixed Canopy (%Area)					
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock					
Unconsolidated Geology					

Percent Gravel Substrate

Percent area in igneous rock type was significant at all scales except the network scale, showing a positive relationship in each (Table 9). Topographic complexity was significant in all but the segment scale, negatively related to percent gravel substrate in each. Mean channel slope was significant at the network and segment scale, also negatively related to percent gravel substrate. Drainage density was significantly related to percent gravel substrate at the basin, network, and sub-basin scale. Interestingly, drainage density was positively related to percent gravel substrate at the basin and sub-basin level but negatively related at the network level. Channel slope, significant in the network and segment models, was negatively related to percent gravel substrate. Area of analysis unit showed a significant positive relationship to gravel substrate at the sub-basin and sub-network scale.

Percent Cobble Substrate

Topographic complexity, significant in the basin, network, sub-basin, and sub-network models, was positively related to percent cobble substrate in each (Table 10). Drainage density was significant at the basin and sub-basin scale, negatively related to percent cobble substrate in both. Percent area with between 31 and 65% slope was significant only at the segment scale and showed a positive relationship with percent cobble substrate. Compactness coefficient and percent area in slope over 65% were significant only in the basin scale model with a negative and positive relationship with percent cobble, respectively. Analytical Unit Area was significant only in the sub-basin model, showing a negative relationship with percent cobble substrate.

Percent Sand, Silt and Organics in Substrate

Topographic complexity was significant in all five models, showing a negative relationship with percent sand, silt, and organic substrate composition (Table 11). Percent area in slope greater than 65% slope was significant in the network, sub-basin, sub-network, and segment models and showed a negative relationship with percentage sand, silt, and organic substrate. Analysis unit area was significant for the sub-basin and segment models and showed a positive relationship to the dependent variable. Drainage density was significant in the basin and sub-basin models with a positive relationship. Percent area with igneous rock types was significant in the basin and network models with positive correlations in each model. Compactness coefficient and percent area with over 65% slope were significant in the basin scale only with positive and negative relationships, respectively. Percent area in broadleaf canopy was significant in only the sub-basin model and showed a negative relationship.

Percent Bedrock Substrate

Drainage density was significant in the basin, sub-basin, and segment scale models. Drainage density showed a negative relationship to bedrock substrate percentage at the basin and sub-basin scales and a positive relationship at the segment scale (Table 12). Percent area with slope over 65% was significant at the sub-basin, subnetwork, and segment scales, showing a positive relationship with bedrock percentage. Unconsolidated material was significant at the network and sub-basin scales, with a negative relationship with percentage bedrock. Topographic complexity and percent area in igneous rock types were significant only in the network-scale model, showing a positive and negative relationship, respectively. Area of analytical unit, relief ratio, percent area with slope between 31 and 65%, and percent area in metamorphic rock types were significant only in the basin scale model. Analytical Unit Area, relief ratio, and percent area in slope between 31% and 65% were positively related to percentage bedrock while percent area in metamorphic rock showed a negative relationship. Percent area with unconsolidated geology was significant in the network and sub-basin models, showing a negative relationship with percentage bedrock in each one.

Table 9

Unstandardized Coefficients for Percent Gravel Substrate Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	**Networks**	**Sub-Basins**	**Sub-Networks**	**Segments**
(Constant)	3.212	4.858	2.264	1.711	3.932
Analysis Unit Area			.110 (.292) [*Ln*]	.146 (.384) [*Ln*]	
Compactness Coefficient			-.443 (-.131) *		
Channel Slope		-.003 (-.340)		-.003 (-.122) *	-.005 (-.200)
Drainage Density	125.743 (.353)	-97.044 (-.116)	92.245 (.278)		-26.613 (-.120) *
Relief Ratio	-.367 (.201)				
Topographic Complexity	-.001 (.001)	-.003 (-.340)	-.003 (-.268)	-.004 (-.366)	
Slope < 30% (% Area)					
Slope 31 - 65% (% Area)					-.695 (-.255)
Slope > 65% (% Area)					
Open/Semi-Closed Canopy (% Area)					
Broadleaf Canopy					
Mixed Canopy (%Area)					
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock	-.194 (.077)	-.141 (-.118) *	-.179 (-.159)	-.204 (-.181)	-.203 (-.188)
Unconsolidated Geology			.495 (.128) *		

Table 10

Unstandardized Coefficients for Percent Cobble Substrate Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	Networks	Sub-Basins	Sub-Networks	Segments
(Constant)	37.979	9.454	62.433	29.745	19.588
Analysis Unit Area			-2.702 (-.306)		
Compactness Coefficient	-11.962 (-.161)				
Channel Slope					
Drainage Density	-2382.134 (-.295)		-2029.550 (-.261)	-1263.131 (-.121) *	
Relief Ratio					
Topographic Complexity	.062 (.290)	.090 (.406)	.093 (.383)	.065 (.016)	
Slope < 30% (% Area)					
Slope 31 - 65% (% Area)		12.857 (.112) *			13.067 (.205)
Slope > 65% (% Area)	13.524 (.113)				
Open/Semi-Closed Canopy (% Area)					
Broadleaf Canopy					
Mixed Canopy (%Area)					
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock					
Unconsolidated Geology					

Table 11

Unstandardized Coefficients for Percent Sand, Silt, and Organic Substrate Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	**Networks**	**Sub-Basins**	**Sub-Networks**	**Segments**
(Constant)	-2.073	10.654	.500	5.630	.129
Analysis Unit Area			.306 (.199) [*Ln*]		.370 (.161) [*Ln*]
Compactness Coefficient	19.337 (.183)				
Channel Slope					
Drainage Density	2815.217 (.236)	-380.588 (-.111) *	362.472 (.267)		
Relief Ratio					
Topographic Complexity	-.092 (-.302)	-.017 (-.441)	-.015 (-.360)	-.010 (-.246)	-.015 (-.227)
Slope < 30% (% Area)					
Slope 31 - 65% (% Area)	-40.009 (-.235)				
Slope > 65% (% Area)		-5.685 (-.283)	-3.925 (-.230)	-4.762 (-.290)	-3.293 (-.265)
Open/Semi-Closed Canopy (% Area)			-.887 (-.116) *		
Broadleaf Canopy			-1.764 (-.154)		
Mixed Canopy (%Area)					
Sedimentary Rock (% Area)					
Metamorphic					
Igneous Rock	8.826 (.216)	.743 (.152)			
Unconsolidated Geology				-1.659 (-.110) *	

Table 12

Unstandardized Coefficients for Percent Bedrock Substrate Models at All Scales. Numbers in parenthesis are standardized betas. [Ln] denotes natural logarithmic transformation of variable. Asterisks denote insignificant variables (p<.05).

	Basins	Networks	Sub-Basins	Sub-Networks	Segments
(Constant)	-60.649	-19.529	20.708	-2.850	3.005
Analysis Unit Area	4.373 (.383) [*Ln*]				
Compactness Coefficient					
Channel Slope					
Drainage Density	-2042.438 (-.240)	2730.106 (.137) *	-1859.171 (-.235)	1395.185 (.131) *	982.320 (2.741)
Relief Ratio	25.060 (.328)				
Topographic Complexity		.072 (.322)		.035 (.143) *	.055 (.139) *
Slope < 30% (% Area)					
Slope 31 - 65% (% Area)	17.323 (.225)				
Slope > 65% (% Area)			18.516 (.186)	16.644 (.174)	16.261 (.223)
Open/Semi-Closed Canopy (% Area)					
Broadleaf Canopy					
Mixed Canopy (%Area)					
Sedimentary Rock (% Area)					
Metamorphic	-38.871 (-.148)				
Igneous Rock	-3.652 (-.125) *	-4.484 (-.157)			
Unconsolidated Geology		-15.376 (-.152)	-13.119 (-.142)		

Analysis and Discussion

Numerous relationships between stream habitat and landscape variables were demonstrated at multiple scales through multiple regression analyses. The strongest relationships (*R^2*) between geomorphic and stream variables were shown in the models for mean depth, mean width, and percent sand, silt, and organic substrate composition. While differing relationships were shown by analysis at each scale, certain geomorphic variables appear to operate more or less independently of scale for certain variables. Analysis unit area, topographic complexity, percent area of open and semi-closed canopy, and drainage density consistently showed less sensitivity than other geomorphic variables to changes in the scale of analysis.

For the mean stream depth, mean width, and width-to-depth ratio variables, the area of analysis units showed a positive relationship to the variation in those variables at all scales of analysis. This may be attributed to the assumption that larger basins and riparian areas have greater stream discharge, leading to stream segments that are wider and deeper (Burnett et al. 2006). Similar findings have been reported by Lanka et al (1987), and Burnett et al. (2006). Additionally, analysis unit area had higher relative strength than other variables in most models. Topographic complexity was shown to be a significant factor at three or more scales in three out of four substrate type models. Percent of gravel substrate was negatively related to topographic complexity at the basin, network, sub-basin, and subnetwork scales, having more weight at the network and sub-network scales. Percent of silt, sand and organic substrate was negatively related to topographic complexity at all scales. That gravel and finer scale sediments decrease as topographic complexity increases suggests that a positive relationship may exist between topographic complexity and stream power. Platts (1979) found that increased stream order (associated with increased stream discharge) led to a decrease in gravel substrate. A positive relationship between percent cobble substrate and topographic complexity at all but the segment scale further suggests the link between topographic complexity and stream power, since the absence of smaller sized substrate materials may be attributed to increased discharge. The positive relationship between topographic complexity and mean depth at the network, sub-basin, and sub-network scales also suggests the same.

Percent area of open and semi-closed forest canopy was also significant across multiple scales in the mean depth, mean width, and percent shade models, negatively affecting those variables. That percent of shade provided to habitat units decreases with an increasing percentage of open area and reduced canopy seems intuitive; however, an explanation of the negative relationships between open areas and the mean depth and width models is not as apparent. Burnett et al. (2006) showed a negative relationship between open and semi-closed canopy and the mean density of large wood in pools in streams. While density of wood debris was not accounted for in this study, it suggests a link between open/semi-closed canopy cover and stream depth and width. Large wood debris contributes to stream morphology by impeding the flow of water to create pools, thereby increasing the width and depth of habitat units (Yarnell et al. 2006). A decreased presence of canopy cover, by reducing the supply of wood debris to the stream, may reduce the amount of slow-water stream reaches otherwise created by the scour and fill action attributed to wood debris.

Drainage density was present in all models of substrate type at differing scales. There was a positive relationship between drainage density and percent gravel substrate as well as percent sand, silt, and organics at the basin and sub-basin scales. Both positive and negative relationships were shown between drainage density and percent bedrock. At the basin and sub-basin scales, percent bedrock substrate is negatively related to drainage density while the relationship is positive at the segment scale. An explanation of the varying direction of the relationships between drainage density and substrate composition is not clear. It is possible that a relationship between drainage density, stream power, and sedimentation rates may explain the presence or absence of smaller sized substrate materials. However, such speculation is beyond the scope of this study.

Substrate Material and Landscape Characteristics

Percent of bedrock substrate was negatively associated with percent area of unconsolidated geologic material at the network and sub-basin scale. The unconsolidated material variable describes geology of predominantly landslide debris and sand. One possible explanation for this relationship may simply be that the presence of unconsolidated material instead of solid rock at the network and sub-basin scales limits the exposure of bedrock in stream channels. However, percent area of igneous intrusive rock types at the network scale is negatively related to percent of bedrock substrate. Turowski et al. (2009) demonstrated that streams with lower relative sediment supply typically had wider and shallower bedrock channels and narrower, more incised bedrock with increased sediment supply. Higher sediment supply provided more erosive material, leading to increased incision in the stream channel. It is possible that the percent of bedrock in stream channels depends more upon variables related to stream power than geologic material. Percent area with slopes over 65% showed a positive trend with percent bedrock at the sub-basin, sub-network, and segment scale. Higher slope leads to increased discharge and higher erosive power. Higher erosion rates associated with steeper slopes at intermediate and fine scales may explain an increase in bedrock exposure. Interestingly, the direction of the relationship between drainage density and bedrock substrate at the segment scale is positive, but negative at the basin and sub-basin scale. The change in direction may reflect the fact that higher drainage density in riparian areas is related to increased streambed scouring, while higher drainage density in basins and sub-basins yield higher sedimentation rates and increased bed load in streams. The relationship between drainage density and gravel and finer sediments is opposite that of bedrock. Drainage density shows a positive trend with both the percent of gravel and percent of sand, silt and organics at the basin and sub-basin scales, while a negative trend is detected at the network scale for both substrate types at the network scale. Furthermore, drainage density is negatively related to percent cobble substrate at the basin and sub-basin scales, implying a higher relative presence of smaller sized alluvium. While a pattern is evident between geomorphic variables and substrate type, the relationship between substrate type and geologic material warrants further research.

Percent of Shaded Habitat Unit and Landscape Characteristics

As expected, the percentage of shade provided to habitat units was negatively influenced by the amount of open and semi-closed canopy cover at all five scales. Percent area with over 65% slope showed a positive trend with percent shade to streams at all scales of analysis, reflecting the influence of topography in providing shade to habitat units. Drainage density was negatively related to percent of shade at the sub-basin and sub-network scale and is likely the result of an increased number of habitat units exposed to the sun since higher drainage density is typically associated with greater variation in the orientation of streams. At the basin scale, relief ratio showed a positive relationship with the amount of shade provided to habitat units, suggesting that average basin slope may influence the amount of solar radiation received in streams.

Spatial Scale and Explanatory Power

In general, models for larger spatial extents demonstrated higher explanatory power than those for smaller extents. This was most evident for the models of substrate type. This increase in explanatory power was most evident for models of percent sand, silt, and organics in substrate. The progressively higher explanatory power suggests that explanatory variables related to processes responsible for variation in fine-grained substrate materials were more fully incorporated into models for larger spatial extents. For example, vegetation cover may be near 100% in most models when analyzed at the riparian extent while analysis at larger spatial extents can show more variability and therefore may be more apt at explaining variability in the substrate models mentioned. Although a decrease in explanatory power with finer scales occurred, some variables that could be operating at those scales were not included in the models for larger spatial extents due to multicollinearity detected at the finer extents. A positive relationship was shown for percent broadleaf canopy cover at the sub-basin scale, but its effect was not detected in other models for the percent sand, silt, and organic models. Percent igneous rock in basin and network scale models showed a positive relationship with the sand, silt, and organic model but its effect was absent or insignificant in other models. The effect of drainage density was detected at the basin, network, and sub-basin scale, but not the finer scales.

Summary and Conclusion

The aim of this thesis was to identify relationships among various landscape and geomorphic characteristics within watersheds and their associations with stream habitat variables. These relationships were studied at multiple scales of analysis in order to account for potential scale dependencies inherent to these characteristics and related processes. Certain expected outcomes were confirmed. For example, mean stream depth shows a significant positive relationship with variables such as drainage density and drainage basin area, which can be explained by inferring the relationship between catchment area and the erosion potential afforded to higher-order streams within larger basins. The most prevalent relationships area summarized below.

Study Limitations

Limitations on time and resources did not permit accounting for spatial autocorrelation between stream variables and landscape characteristics. However, a similar study using similar methods detected very little spatial autocorrelation between these variables, so no attempt was made to remove or account for it in regression models (Burnett et al. 2006). Additionally, low correlation coefficients for certain models may be attributed to misspecification error despite the inclusion of a wide variety of landscape variables in those models. Compromises in data quality due to the limitations in the availability of data in consistent spatial scales and resolution may have affected the accuracy of results due to the fact that landscape characteristics that operate at a finer scale than is 'visible' in the available data were undoubtedly missed. Aggregating stream habitat data by using summary statistics for each stream segment could also be potentially problematic, especially for stream segments of longer lengths.

Dominant Relationships

Linkages between geomorphic variables and stream dimensions were found at all extents of analysis. Among the most influential explanatory variables was analytical unit area size, topographic complexity, percentage area of open and semi-closed canopy coverage, drainage density and, in several cases, the slope of analytical unit areas. Mean depth and width of streams was shown to increase with the size of analytical unit area across all spatial extents for depth and all but one for width. As noted earlier, this relationship could be expected due to the increased stream power afforded by larger drainage basin and/or riparian area sizes. Interestingly, mean width and depth decreased with larger areas of open and semi-closed canopy. One possible reason for the inverse relationship between stream dimensions and open areas could be the increased sedimentation and aggradation of streambeds that can occur in areas of decreased vegetation, such as open pasture and other developed areas. Mean depth and width were shown to increase with higher topographic complexity, or the standard deviation of elevation, across almost all analytical scales.

More correlations between landscape and/or geomorphic variables and stream habitat characteristics such as the amount of shade provided to habitat units and the composition of stream bed material were also found. The amount of shade provided to habitat units was found to decrease with higher percentages of open and semi-closed canopy coverages, reflecting the role of vegetation in providing, among other things, regulation of temperature in stream habitats via shielding stream habitat from excess insolation (Yard et al., 2005). Percentage shade provided to analytical units was shown to increase with the percentage area of analysis extents with slopes between 31 – 65%, quantifying the role topography plays in providing shade to streams. Models showing this relationship suggest that areas of moderate to moderately steep slope provide more shade than do areas of lower relief. The same models can also be interpreted as suggesting that streams in areas of lower relief can benefit in terms of the amount of shade provided by increased availability of vegetation cover when not provided by topography alone.

Substrate materials were also shown to be correlated with both geomorphic and landcover variables. Interestingly, geology type was not a significant factor in the majority of models for substrate type. Percentage area in igneous rock types was modeled to decrease the percentage of gravel substrate at every spatial extent. The lack of meaningful models relating geology types may be due to the level of detail available in the dataset used. Topographic complexity, on the other hand was significantly correlated with all substrate types but bedrock. The percentage of gravel and cobble substrate types increased with higher topographic complexity while sand, silt, and organics decreased. Various relationships were shown between drainage density and substrate models. For example, the percentage of gravel substrate increases with higher drainage density at the basin and sub-basin scales, but decreases at the network scale. Cobble substrate decreases with increasing drainage density at the basin and sub-basin extents, but increases at the segment scale. As noted in the discussion chapter, the link between drainage density and stream power is evident in these models, quantifying how drainage density may influence streambed material at varying scales. Areas of steep (> 65%) slope were a significant factor in the bedrock and sand/silt/organic substrate models. Bedrock was modeled to increase with steeper slopes, while sand/silt/organic substrates decreased at all analysis extents. Again, a fairly intuitive relationship between streambed material and slope are suggested in these models.

Conclusion and Future Research Considerations

This thesis suggests the scale dependency of linkages between landscape and geomorphic properties of watersheds and stream morphology. By partitioning data into varying extents, it is possible to detect those relationships and determine their relative strengths (or lack thereof). By determining the sensitivity of those relationships to varying spatial extents, this study suggests that processes that otherwise may have been deemed insignificant using a fixed extent of analysis can be accounted for by determining the scale at which at it operates.

While variations in relationships with scale were revealed here, the interaction of landscape variables across varying scales was not determined due to time constraints. It is quite possible that relationships among geomorphic and landcover variables that appear weak when quantified within each of the five spatial scales may interact with properties quantified at smaller or larger extents. Multiple regression analyses among variables summarized at differing scales can provide numerical evidence of those complex interactions. Models by Burnett et al. (2006) suggest that such interactions are quantifiable, although the sample size for the study was limited to fifteen stream segments. Perhaps by increasing sample size and using a wider array of explanatory variables at a finer resolution, such among-scale relationships can be further illuminated. The accessibility of higher resolution data currently increases at a fairly rapid pace, which will allow a much higher level of detail (especially of terrain data) to be utilized in studying the relationship between catchment landscape and the hydraulic and geomorphic properties of stream habitats.

In addition to modeling the purely physical parameters of watershed-to-stream linkages, it would be extremely useful to model the relationship among landscape and geomorphic properties of the landscape and stream to the utilization of specific habitat by aquatic species. Modeling migration patterns of anadromous species against both landscape and stream variables at multiple scales could provide more insight into linkage between the physical and behavioral. Furthermore, such studies could prove to be useful in assessing the effects of watershed restoration efforts over a period of time. The addition of the temporal scale would prove to be valuable not only in determining the before- and after effects of watershed and stream habitat modification, but could also provide insight into the recovery time involved in affected areas and allow the assessment and isolation of key landscape and geomorphic variables vital to the response at various spatial and temporal extents.

The advantages allowed by geospatial software in multi-scale analyses of landscape patterns and their relationship to stream conditions can be used to aid in better targeting of conservation and land-use practices in sensitive watersheds such as those in the Pacific Northwest. Moreover, determining more accurately across which scales and to what degree processes act across a landscape, it may be possible to develop predictive models that could complement more traditional watershed health assessments. The increasing availability and quality of remotely sensed data can improve the efficiency, cost, and practicality of such assessments.

References

Allan, J.D., Erickson, D.L., & Fay, J. (1997). The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology, 37*, 149 – 161.

Allan, J.D., & Johnson, L.B. (1997). Catchment-scale analysis of aquatic ecosystems. *Freshwater Biology, 37*, 107 – 111.

Aquatic Inventories Project Habitat and Reach Data Coverages Metadata. *Oregon Dept. of Fish and Wildlife*: February 2004.

Burnett, K., Reeves, G.H., Clarke, S.E., & Christiansen K.R. (2006). Comparing riparian and catchment influences on stream habitat in a forested, montane landscape. *American Fisheries Society Symposium, 48*, 175 – 197.

Burnett, M.R., August, P.V., Brown, J.H., & Killingbeck, K.T. (1997). The influence of geomorphological heterogeneity on biodiversity: I. A patch scale perspective. *Conservation Biology, 12 (2)*, 363 – 370.

FEMAT (1993). Forest Ecosystem Management: An Ecological, Economic and Social Assessment. *USDA Forest Service, BLM, USFWS, NOAA, EPA and National Park Service*. Portland, Oregon.

Gorman, O.T., & Karr, J.R. (1978). Habitat structure and stream fish communities. *Ecology, 59 (3)*, 507 – 515.

Hay, G. J., Marceau, D. J., Dubé, P., & Bouchard, A. (2001). A multiscale framework for landscape analysis: object-specific analysis and upscaling. *Landscape Ecology,16 (6)*, 471 – 490.

Hay, G. J., Marceau, D. J., Dubé, P., & Bouchard, A. (2002). Modeling multiscale landscape structure within a hierarchical scale-space framework. *Symposium on Geospatial Theory, Processing and Applications, Ottawa*.

Huryn, A.D., & Wallace, B. (1987). Local geomorphology as a determinant of macrofaunal production in a mountain stream. *Ecology, 68 (6)*, 1932 – 1942.

Jelinski, D.E., & Wu, J. (1996). The modifiable areal unit problem and implications for landscape ecology. *Landscape Ecology, 11*, 29 – 140.

Lanka, R.P., & Wesch, T.A. (1987). Relations of geomorphology to stream habitat and trout standing stock in small Rocky Mountain streams. *Transactions of the American Fisheries Society, 116*, 21 – 28.

Li, H., & Reynolds, J.F. (1994). A simulation experiment to quantify spatial heterogeneity in categorical maps. *Ecology, Vol.75 (8)*, 2446-2455.

Lunetta, R.S., Cosentino, B.L., Montgomery, D.R., Beamer, E.M., & Beechie, T.J. (1997). GIS-based evaluation of salmon habitat in the Pacific Northwest. *Photogrammetric Engineering & Remote Sensing, 63 (10)*, 1219-1231.

Marceau, D.J., & and Hay, G.J. (1999). Contributions of remote sensing to the scale issue. *Canadian Journal of Remote Sensing, 25 (4)*, 357 – 366.

Moore, K., Jones, K., & Dambacher, J. (2002). Methods for stream habitat surveys. *Oregon Department of Fish and Wildlife, Aquatic Inventories Project, Natural Production Program, Corvallis, OR*.

Morse, J.C., Stark, B.P., & McCafferty, P. (1993). Southern Appalachian streams at risk: Implications for mayflies, stoneflies, caddisflies, and other aquatic biota. *Aquatic Conservation: Marine and Freshwater Ecosystems, 3*, 293-303.

Nichols, W.F., Killingbeck, K.T., & August, P.V. (1998). The influence of geomorphological heterogeneity on biodiversity: II. A landscape perspective. *Conservation Biology, 12 (2)*, 371 – 379.

Petts, G.E., & Gurnell, A.M. (2005). Dams and geomorphology: research progress and future directions. *Gemorphology, 71*, 27 – 47.

Platts, W.S., 1979. Relationships among stream Order, fish populations, and aquatic geomorphology in an Idaho river drainage. *Fisheries, 4 (2)*, 5 – 9.

Potter, K.M., Cubbage, F.W., & Schaberg, R.H. (2005). Multiple-scale predictors of benthic macroinvertebrate community structure in North Carolina. *Landscape and Urban Planning, 71*, 77 – 90.

Power, M.E. (1992). Habitat heterogeneity and the functional significance of fish in river food webs. *Ecology, 7 (5)*, 1675 – 1688.

Vidon, P.G.F., & Hill, A.R. (2004). Landscape controls on the hydrology of stream riparian zones. *Journal of Hydrology, 292*, 210 – 228.

Ward, J.V. (1998). Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation, 83 (3)*, 269 – 278.

Ward, J.V., & Tockner, K. (2001). Biodiversity: toward a unifying theme for river ecology. *Freshwater Biology, 46*, 807-819.

Yard, M., Bennett, G.E., Mietz, S.N., Coggins, L.G., Stevens,L.E., Hueftle, S., & Blinn, D.W. (2005). Influence of topographic complexity on solar insolation estimates for the Colorado River, Grand Canyon, AZ. *Ecological Modeling, 183 (2-3)*, 157-172.

Yarnell, S.M., Mount, J.F., & Larsen, E.W. (2006). The Influence of relative sediment supply on riverine habitat heterogeneity. *Geomorphology, 80*, 310 – 324.